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High Resolution CCD Spectra of Stars in Globular Clusters II: Metals and CNO in M71

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Abstract

We have used Palomar coudé CCD spectra of resolution 0.3 and 0.6 Å to redetermine abundances in five stars of the relatively metal rich globular cluster M71. The [Fe/H] value is restricted to the limits of −0.6 to −1.0. The largest source of uncertainty is a systematic difference in f-values between those derived via the Holweger-Muller (1974) solar model and the Bell *et al.* (1976) solar model. If we use absolute f-values measured by the Oxford group (Blackwell *et al.* 1982) we find [Fe/H] to lie in the range of −0.6 to −0.75, *i.e.*, as given by using the Bell *et al.* solar model.

The relative abundances of the light elements, *i.e.*, Na through Ca and probably including Ti show an average excess relative to iron of 0.4 dex. We discuss the effect of this difference on metal indices derived from broad band and narrow band photometry.

For three stars we find [O/H] = −0.6 using absolute f-values. For CN an analysis of individual rotational lines of the 2–0 band of the red system yields lines in the (C/H, N/H) plane that are consistent with either an original [C/Fe] = [N/Fe] = 0 or a modest increase in N relative to C due to CN burning and mixing. A search for ^{13}CN was not successful and an uncertain lower limit of $^{12}C/^{13}C$ near 10 was obtained.

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I. Introduction

The chemical composition of stars in the globular clusters of least metal deficiency has been controversial since surprisingly large iron deficiencies. [Fe/H] = −1.3 and −1.2 were reported for M71 and 47 Tuc, respectively (Cohen 1980; Pilachowski *et al.* 1980: Pilachowski *et al.* 1983. henceforth PSW). These values have been challenged by analyses of broad-band and narrow band photometry which indicated that the overall metal abundance, a mean of those elements whose lines contribute to the blanketing within the observed bands weighted by the contribution of each element, was closer to [M/H]= −0.6 and −0.7 for M71 and 47 Tuc, respectively. (Zinn and West 1984).

Bell and Gustafsson (1982) analyzed the Searle and Zinn (1978) as well as DDO photometry of M71 stars and found [M/H]=−0.6, while their reanalysis of Cohen's (1980) data yielded [Fe/H]=−0.9. They recognized the difference between the general metal abundance as derived from broad bands and the iron abundance as derived from individual lines. This difference has also been discussed in some detail by Butler, Dickens and Epps (1978) in their survey of stars in ω Cen. Unfortunately, some authors have considered iron to represent all elements heavier than neon, but detailed studies show this to often not be the case.

In an effort to clarify the situation Cohen (1983) obtained CCD spectra of stars in M71 with very high signal-to-noise at the Cassegrain double spectrograph on the 5-meter Hale telescope. Those spectra, which have a resolution about 0.7 Å, yielded an iron abundance [Fe/H] = -0.75 ± 0.1 for M71.

Additional analyses of M71 from spectra with a resolution of 0.3 Å and a signal-to-noise between 22 and 30 by Pilachowski. Olszewski and Odell (1983) yielded [Fe/H] = −1.0 (or possibly as high as −0.8) from a 60 Å interval in two stars. Their stars are sufficiently hot that no problems with molecular line blanketing is to be expected (Geisler 1986).

Because of the importance of the problem of the abundance scale of globular clusters

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we have returned to the M71 problem using the Palomar coudé spectrograph and the CCD detector described in paper I of this series.

Spectra of resolution 0.3 Å were obtained in the 6100–6200 Å and 6300–6400 Å regions while spectra of resolution 0.6 Å were recorded in the 7800–8000 Åand 8600–8800 Å regions. The latter spectra were obtained in August 1985 with the 0.9-m camera rather than the 1.8-m camera and hence provided 220 Å of spectrum rather than 110 Å. In Table 1 we show data for each star observed and a summary of the available spectra. Membership probabilities are from Cudworth (1985); colors are from Frogel, Persson and Cohen (1979) and Cudworth. Effective temperatures are on the Cohen, Frogel and Persson scale, combined with Ridgway *et al.* (1980) and Blackwell *et al.* (1986, for Arcturus). As pointed out by Trimble and Bell (1980), the temperature scale for K giants is uncertain by at least 100 K, leading to an uncertainty in [Fe/H] of a little less than 0.1. The value of log g is from the luminosity and effective temperature, and the assumption that $M = 0.8\ M_{\odot}$ for each star. In the seventh column we list the derived turbulent velocity, V_t.

II. The Analysis

a. Atomic Lines

The analysis was carried out using model atmospheres and spectrum synthesis in the same way as was done in Paper I. However, because of the need to obtain abundances relative to the sun, we decided to use solar gf values for all lines except [OI], Rb I and Zr I.

The iron abundance is crucial in most discussions of the abundance scale in globular clusters. Hence, we have been very careful in deriving the log gf values for FeI. First, we used the solar equivalent widths in Moore, Minnaert and Houtgast (1966) combined with the Holweger and Muller (1974) (hereafter HM) solar model and a solar iron abundance of log N(Fe) = 7.50 on a scale of log N(H) = 12.0. The derived f-values are quite sensitive to the solar model that is used (Pilachowski *et al.* 1983).

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There are a few other special concerns. For OI we used the f-value of Lambert (1978) and assume a low enough carbon abundance so as not to be affected by CO formation. For Rb I we employed the laboratory gf value of Reader *et al.* (1980). For Zr I we have used f-values from Biemont *et al.* (1981) plus one line from Corliss and Bozman (1962) that we corrected to the Biemont *et al.* scale.

As in paper I, we used the models of Bell *et al.* (1976) (hereafter BEGN) and a modified form of the spectral synthesis program MOOG (Sneden 1973). In the first approximation we used models with a metal abundance parameter of -1.0 dex. In the final calculation we adjusted this to reflect the abundances of Fe, Si and Mg, which are the principal electron contributors. Unfortunately, our Mg abundance is very uncertain, so we represented Mg by the mean of our Si, Ca and Mg abundances. The overall effect of changing the input metal abundance from -1.0 to -0.7 dex is to increase the final abundances of all neutrals by 0.05 dex. This change in abundance has been included in the values in Table 2, where we list the abundance as derived from each line of each star.

b. The CN Lines

We first searched for CN lines in the λ6100 region, but the lines were so weak that it was deemed essential to reobserve M71 at the (2,0) band of the $A\ ^2\pi\ -\ X^2\sum$ system in the 7800–8000 Å region. Observations of three M71 stars were obtained in August 1985. Because of the limited resolution – about 0.6 Å – we chose to obtain a signal-to-noise of at least 100 by recording at least 10^4 counts per channel in all spectra. We also obtained spectra in the 8600–8800 Å region for the (3, 1) and (4, 2) bands, just in case the CN lines of the (2,0) band were too strong and to observe the CI line at λ8727. The latter was searched for but could not be identified conclusively at our resolution. No really useful lines of ^{13}CN were found.

The gf values for the CN lines were calculated as described by Dominy, Wallerstein and Suntzeff (1986). Band oscillator strengths were taken from Larsson, Siegbahn and Agren

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(1983). A recent paper by Davis *et al.* (1986) questions the results of Larsson *et al.* (1983). Davis *et al.* gives a value of 7.60E-04 for CN(2.0), while Larsson *et al.* give 12.50E-04. Using the Davis *et al.* oscillator strengths increases our present results for CN(2.0) by 0.22 dex.

III. Derived Abundances

a. Iron

Our mean iron abundances for each star are shown in Table 3, where we include our analysis of Arcturus for comparison. By using all lines available in each star we derive the values shown in the first group. If we restrict ourselves to lines in common between M71 stars and Arcturus we find the values in the second group. For three stars in M71 there is a substantial difference in [Fe/H] because we have included 13 FeI lines in the 8600-8800 Å region. The mean values of [Fe/H] (using the HM solar model) are −0.98 if we include all lines, −0.88 if only lines in common with Arcturus are used. For Arcturus we find [Fe/H] = −0.75, using the HM solar model to derive f-values, and [Fe/H] = −0.50 for f-values from the BEGN model. The BEGN value for Arcturus is close to most published values. For nine determinations published after 1965 listed by Cayrel de Strobel *et al.* (1985) we find [Fe/H] = -0.49 ± 0.04. Our iron abundance for Arcturus is somewhat lower than the mean of other determinations because we used a somewhat lower effective temperature (Blackwell *et al.* 1986) and slightly higher turbulence parameter than average. The small dispersion in [Fe/H] despite the wide range in atmospheric parameters for Arcturus is surprising (Trimble and Bell 1981). The similarity of M71, star I, and Arcturus is illustrated in Fig. 1.

A comparison of Tables 1 and 3 shows that our two coolest stars yield significantly lower iron abundances than do the three stars whose temperature is closer to that of Arcturus. This is probably due to the effects of TiO on the continuum of the coolest stars (Geisler 1986) and departures from LTE in the ionization equilibrium (PSW). Hence, we

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show the mean iron abundances for M71 from the three hottest stars only as a separate row in Table 3. The difference is about 0.1 dex.

We are uncertain why our data for the 8600–8800 Å region yields such low abundances. There are few strong CN lines in this region and almost no atmospheric lines to disturb the continuum. However, some lines we used from this region have solar equivalent widths near the flat part of the curve of growth, although in all cases log $W/\lambda \leq -4.90$. To check if the solar equivalent widths in Moore *et al.* (1966) are in error, we used the new solar flux atlas by Kurucz *et al.* (1984) to recalculate equivalent widths. The match was excellent. Next, we used Oxford gf values (Blackwell 1982) and recalculated the abundances. The results were similar to those found using BEGN solar gf values.

Returning to Table 3 and looking only at the group of lines in common with Arcturus, we see mean values of [Fe/H] for M71 which range from −0.59 to −0.70 (BEGN). We quote no internal errors because they are deceptively small in the light of the uncertainties in the metal abundance of Arcturus and the range of solar f-values that are derived from different solar models and the same solar equivalent widths. We have also used absolute f-values as determined by Corliss and Tech (1968) (hereafter CT) as modified to fit the more recent experiments of Blackwell *et al.* (1982). The resulting iron abundances fall within the range quoted above. Notice that the values derived from the BEGN model and the CT calculation are in excellent agreement. It appears that values of [Fe/H] ranging from −0.6 to −1.0 can be derived from the data. We defer until § V a discussion of our "preferred" value within this range. Considering that uncertainties inherent in the analysis of Arcturus, given the excellent data in the Arcturus Atlas (Griffin 1968), are similar with the range of [Fe/H] from −0.32 to −0.7 (Cayrel de Strobel *et al.* 1985), we do not see how a more precise value of [Fe/H] can be claimed for stars in M71. For a full analysis of the problem of determining atmospheric parameters for Arcturus see Trimble and Bell (1981).

b. Carbon, Nitrogen, and Oxygen

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Our analysis of these light elements is independent of solar gf-values because we used absolute transition probabilities. For the three stars observed in the $\lambda 6300$ region we find a mean value of $[O/H] = -0.61 \pm 0.06$; the quoted uncertainty being internal. At the high end of our iron abundance we obtain $[O/Fe] = 0.0$, while at the low end $[O/Fe] = +0.4$. To use the CN lines to derive a relationship between the carbon and nitrogen abundances, we must use the derived oxygen abundance in the molecular equilibrium equations. The CN lines then yield a relationship between the carbon and nitrogen abundances shown in Fig. 2, where the axes are the logarithms of the absolute C/H and the N/H ratios. In the sun these quantities are -3.4 and -4.0, respectively. Since we could not detect the CI line at $\lambda 8727$, we have no purely empirical method to decide where the C and N abundances of the three M71 stars lie. However, we show the lines defined by C=N and C=3N, which mark the range of C/N ratios for K giants with moderate metal deficiencies observed by Lambert and Ries (1981). In addition, we show the line of possible initial C and N abundances, assuming $[C/Fe] = [N/Fe] = 0$. An analysis of the CH bands would be valuable.

We have endeavored to establish the $^{12}C/^{13}C$ ratio in these stars by observation of the ^{13}C features near 8003 Å. For Arcturus, whose $^{12}C/^{13}C$ ratio is 7, the line is present on our spectra. The line appears to be present in one star in M71, but is displaced in two other stars. It is best not to claim a detection, but rather, to use the feature to give us a rough lower limit of about 10.

c. Abundances Relative to Iron of Sodium through Lanthanum

We now turn to other elements between sodium and lanthanum. For elements with few useable lines it is not useful to quote an internal probable error on the basis of the observed scatter around the mean. We feel it is more realistic to accept as a probable error the mean error for a single line as determined from all the FeI lines (excluding the lines in the $\lambda 8600$-8800 region) and dividing by $\sqrt{n}$ of each element. We will use 0.20 dex as the

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mean error of a single determination of FeI and proceed accordingly.

In addition to the scatter, we must contend with the uncertainty introduced by the choice between the Holweger and Muller f-values vs. the BEGN f-values. The differences depend upon the ionization potential of the species and the excitation potentials of the lines. This is all best summarized in Table 4, where we show the mean for each element after averaging over all M71 stars in which we observed the line.

It is clear from Table 4 that all elements lighter than scandium are substantially less deficient than are elements from scandium through copper. Titanium may belong to either group. The odd-even effect which is often prominent in metal-poor stars is not evident. A comparison with Arcturus shows the same effect whether we use our data in Table 4 or the results of Mäckle *et al.* (1975).

IV. Discussion

a. The General Metal Abundance of M71

In the previous section we showed that relative to the sun we find [Fe/H] for M71 to lie in the range of −0.6 to −1.0. Of this range of 0.4 dex about 0.2 dex is due to the uncertainty in f-values introduced by the choice of solar model. About 0.1 dex is caused by the inclusion of the lines near λ8800 Å and 0.1 dex is the "random" scatter among the five stars.

The Holweger Müller model of the solar atmosphere is probably preferable because it is an empirical model based on observations. In particular, Sauval *et al.* (1984) find the same solar oxygen abundance from pure rotational features of an OH in the ten μm region as found from the [OI] lines in the visual region. Since the solar opacity is much greater at 10 μm, the OH lines are formed at very small optical depths and are very sensitive to the temperature structure in the outer atmosphere. This causes us to prefer the lower end of the iron abundance scale given above. On the other hand, the BEGN solar model

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was calculated by the same methods as used in the models that represent the red giants in M71. so any errors in methods might appear in both models and hence compensate. Furthermore, the absolute f-values of the Oxford group (Blackwell *et al.* 1982) favors the BEGN values.

The problem can be finessed if we quote only our iron abundance relative to Arcturus and then use the mean $[Fe/H] = -0.49 \pm 0.04$ (Cayrel de Strobel *et al.* 1985). By this method we find M71 to be deficient in iron by 0.10 dex relative to Arcturus or $[Fe/H] = -0.6$ relative to the sun. It appears that the range of -0.6 to -1.0 cannot be narrowed any further at this time.

As noted in the Introduction. it is not correct to assume that iron represents all elements heavier than neon. While iron does seem to represent the iron peak elements rather well, the light elements – Na to Ca (and probably Ti) – show a mean excess relative to iron of 0.4 dex is M71 and 0.3 dex in Arcturus. Hence. the abundance of these elements may be described as ranging from -0.6 to -0.2 dex relative to the sun by our comparison and -0.3 dex by comparison with Arcturus.

Most efforts to derive metal abundances by low resolution methods depend upon observations of broad spectral bands that contain lines of many elements. This fact is probably responsible for at least part of the 0.4 dex difference between high resolution and low resolution determinations quoted by Burstein *et al.* (1986). Broad-band analyses can only be compared with high dispersion analyses if the numerous absorption lines within the band can be divided up among the iron-peak and light metals, which is not an easy job. For example, Burstein *et al.* used two wavelength regions. $\lambda 5270$ and $\lambda 5335$. with 9 Å pass bands. If we take an inventory of all lines listed by Moore *et al.* (1966) between $\lambda 5265.0$ and $\lambda 5275.0$. we find 21 lines from the iron peak. 7 light metal lines and 18 unidentified lines. The unidentified lines range in strength from 1.5 to 31 mÅ.* In the

* It is interesting to note that only 10 of the identified lines in this 10 A interval are

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sun the unidentified lines do not contribute much to the total line blanketing in the pass band, but in Arcturus and the M71 giants most of them are about 10 times stronger while still on the linear part of the curve of growth: hence, they contribute substantially to the *difference* in line blanketing from star to star. For the λ5335 Å band of Burstein *et al.* the inventory between λ5330 and 5340 shows 18 iron peak lines, 5 lines of light metals and 25 unidentified lines ranging from 1 to 8.5 mÅ in equivalent width. In this band, as well as around λ5270, we must be suspicious as to how much differential blanketing is introduced by these unidentified lines.

Since we have fitted theoretical spectra to individual lines identified with specific elements, we believe that our range of [Fe/H] values from −0.6 to −1.0 and of light elements from −0.2 to −0.6 dex is preferable to specific numbers quoted from spectra whose resolution ranges from nine to several hundred Angstroms. The large range of uncertainty that we quote will just have to be lived with (as do a lot of other uncertainties in this complicated world).

b. C, N, and O in M71

Our oxygen abundances depend on absolute f-values and hence do not carry the uncertainty introduced by running solar equivalent widths through a solar model. We find [O/H] = −0.62 ± 0.10 from three stars. This translates into [O/Fe] = 0.0 to 0.4 dex, depending on the iron abundance, which is similar to [O/Fe] in other globular clusters with [Fe/H] in the −0.6 to −1.0 range (PSW).

Our synthesis of ^{12}CN features yields a line in the (C/H, N/H) plane which we show in Fig. 2. By selecting a reasonable range in the C/N ratio we can restrict ourselves to a section of the (C/H, N/H) plane. For red giants with small metal deficiencies Lambert and Ries (1981) find C = 3N for Arcturus and C = N for γLeo A and B. We show these

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stronger than the 31 mÅ unidentified line.

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lines in Fig. 2 and shade in the most likely region of the (C/H, N/H) plane to be inhabited by the M71 red giants.

To understand how these stars got there we must know where they started in the (C/H, N/H) plane. Laird (1985) provides C/Fe and N/Fe ratios for metal-poor field dwarfs. After correcting for small systematic effects, he finds [C/Fe] = [N/Fe] = 0. Combining this with our range in Fe/H yields the line marked in Fig. 2 as "M.S. line". Now CN cycling and mixing always leads to reduced carbon, enhanced nitrogen and reduced $^{12}C/^{13}C$. During normal stellar evolution up the red giant branch the first dredge-up of CN cycled material accomplishes this to a degree that is determined by the depth of mixing. From Fig. 2 we see that only stars starting near the low end of the main sequence line in the (C/H, N/H) plane can reach the shaded area. This argument favors the low iron abundance but we urge caution because of the uncertainties in all the factors involved, as well as the unfortunate fact that the C/N ratio of 3 in Arcturus indicates no mixing while the $^{12}C/^{13}C$ ratio of 7 implies even deeper mixing than predicted by standard theory. Until we understand the evolution of Arcturus it is difficult to make definitive statements about similar stars in globular clusters with less certain abundances.

V. Summary

The arguments in favor of the metal-poor solution, *i.e.*, [Fe/H] = −0.9 or −1.0 are as follows:

1. The Holweger-Muller empirical model of the solar atmosphere is probably preferable to the BEGN model.
2. Our oxygen abundance based on absolute f-values yields [O/Fe]= +0.4 if [Fe/H]= −1.0 in common with other globular clusters and metal-poor giants.
3. The CN data can be understood in terms of CN cycling and mixing if [C/H] = [N/H] = [Fe/H] = −0.9 or −1.0 when the star formed.

The arguments in favor of the metal-rich solution, *i.e.*, $[Fe/H] = -0.6$ or -0.7 are as follows:

1. The BEGN models were used for both the sun and the stars in M71.
2. The laboratory f-values agree more closely with the BEGN solar values.
3. The hotter stars show the higher iron abundances.
4. A comparison with Arcturus yields $[Fe/H]^{M71}_{Arc} = -0.10$ and the average of many determinations for Arcturus is $[Fe/H]^{Arc}_{\odot} = -0.5 \pm 0.1$.

The argument using laboratory f-values and the comparison with Arcturus seem to us a little stronger than any others, so we slightly favor the $[Fe/H] = -0.6$ or -0.7 value for M71, but only on a roughly 60/40 basis. As they used to say at the amusement parks: "You pays your money and you takes your choice."

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REFERENCES

Bell, R. A., Ericksson, K., Gustafsson, B. and Nordlund, A. 1976, *Astr. Ap. Suppl.*, **23**, 37.

Bell, R. A. and Gustafsson, B. 1982, *Ap. J.*, **255**, 122.

Blackwell, D. E., Booth, A. J., Petford, A. D., Leggett, S. K., Mountain, C. M. and Selby, M. J. 1986, *Mon. Not. Roy. Astron. Soc.*, **221**, 427.

Biemont, E., Grevesse, N., Hannaford, P. and Lowe, R. M. 1981, *Ap. J.*, **248**, 867.

Blackwell, D. E., Petford, A. D., Shallis, M. J., and Simmons, G. J. 1982, *M.N.R.A.S.*, **199**, 43.

Burstein, D., Faber, S. M., and Gonzalez, J.J.., 1986, *Ap. J.*, **91**, 1130.

Butler, D., Dickens, R. J. and Epps, E. 1978, *Ap. J.*, **225**, 148.

Cayrel de Strobel, G., Bentolila, C., Hauck, B. and Duquennoy 1985, *Astron. and Astrophys. Suppl.*, **59**, 145.

Cohen, J. G. 1980, *Ap. J.*, **241**, 981.

Cohen, J. G. 1983, *Ap. J.*, **270**, 654.

Corliss, C. H. and Bozman, W. R. 1962, NBS Monog. No. 53.

Corliss, C. H. and Tech, J. L. 1968, National Bureau of Standards Monograph 108.

Cudworth, K. M. 1985, *A. J.*, **90**, 65.

Davis, S. P., Shortenhaus, D., Stark, G., Engleman, R., Phillips, J. G., Hubbard, R. P. 1986, *Ap. J.*, **303**, 892.

Dominy, J. F., Wallerstein, G., Suntzeff, N. B. 1986, *Ap.J.*, **300**, 325.

Frogel, J., Persson, S. E. and Cohen, J. G. 1979, *Ap. J.*, **227**, 499.

Geisler, D. 1986 (preprint).

Griffin, R. F. 1968, A Photometric Atlas of the Spectrum of Arcturus, Cambridge Philosophical Society.

Holweger, H. and Muller, E. A. 1974, *Solar Physics*, **39**, 19.

Kurucz, R. L., Furenlid, I., Brault, J., Testerman, L. 1984, *National Solar Observatory, Atlas No. 1*, University Publisher, Harvard University; Cambridge.

Laird, J. B. 1985, *Ap. J.*, **289**, 556.

Lambert, D. L. 1978, *M.N.R.A.S.*, **182**, 249.

Lambert, D. L., Ries, L. M. 1981, *Ap. J.*, **248**, 228.

Larsson, M., Siegbahn, P. E. M., Agren, H. 1983, *Ap. J.*, **272**, 369.

Leep, E. M., Wallerstein, G. and Oke, J. B. 1986, *A. J.*, **91**, 117.

Moore, C. E. Minnaert, M. G. J. and Houtgast, J. 1966, NBS Monog. No. 61.

Pilachowski, C. A., Canterna, R. and Wallerstein, G. 1980, *Ap. J. Letters*, **235**, L21.

Pilachowski, C. A., Olszewski, E. W. and Odell, A. 1983, *Pub.A.S.P.*, **95**, 713.

Pilachowski, C. A., Sneden, C. and Wallerstein, G. 1983, *Ap. J. Suppl.*, **52**, 241.

Reader, J., Corliss, C. H., Wiese, W. L., and Martin, G. A. 1980. Wavelengths and Transition Probabilities for Atoms and Atomic Ions (NSRDS-NBS 68).

Ridgway, S. T., Joyce, R. R., White, N. M., and Wing, R. F. 1980, *Astrophys. J.*, **235**, 126.

Searle, L. and Zinn, R. 1978, *Ap. J.*, **225**, 357.

Sneden, C. 1973, Ph.D. Thesis, University of Texas.

Trimble, V. and Bell, R. A. 1981, *Quart. J. R.A.S.*, **22**, 361.

Zinn, R. and West, M. J. 1984, *Ap. J. Suppl.*, **55**, 45.

Table 1
Observations of stars in M71

Star	member	(B-V)	(V-K)	Teff (k)	log g	V_t (kms^{-1})	spectral region	continuum counts
I	93%	1.28	-----	4300	0.9	2.0	6100	2,500
							6300	4,000
							7900	16,000
							8700	11,000
A4	94%	1.47	3.55	4100	0.8	2.0	6100	4,000
							6300	4,000
							7900	13,000
							8700	14,000
1-21	95%	1.24	2.84	4400	1.65	2.0	6100	2,200
1-46	93%	1.57	3.64	4050	0.8	2.0	6300	2,700
							7900	15,000
							8700	16,000
1-53	95%	1.36	-----	4325	1.3	2.5	6100	2,500
ARCTURUS		1.23	3.00	4250	1.7	2.4	6100	70,000
							6300	3,000
							7900	42,000

TABLE 2

Elemental Abundances from each Line in each Star in M71 and Arcturus.

	WAVELENGTH	EPLOW	GF(SOLAR)	I	A4	1-21	1-46	1-53	ARCTURUS
O I	6300.317	0.00	1.778E-10	-0.67	-0.67	-----	-0.49	-----	-----
NA I	6154.227	2.09	2.127E-02	-0.27	-0.46	-0.47	----	+0.11	-0.46
NA I	6160.750	2.10	4.399E-02	-0.20	-0.34	-0.46	----	-0.17	-0.46
MG I	7930.823	5.94	4.887E-02	-0.03	-0.11	-----	-0.15	-----	+0.01
MG I	8717.829	5.93	1.973E-01	-0.71	-0.74	-----	-0.73	-----	-----
AL I	7835.306	4.02	1.844E-01	-0.31	-0.35	-----	-0.18	-----	-0.16
AL I	7836.127	4.02	3.727E-01	-0.32	-0.16	-----	-0.34	-----	-0.32
AL I	8772.876	4.00	3.722E-01	-0.24	-0.40	-----	-0.32	-----	-----
AL I	8773.907	4.00	6.608E-01	-0.29	-0.40	-----	-0.38	-----	-----
SI I	6131.852	5.59	1.925E-02	-0.41	-0.48	-0.54	-----	-0.60	-----
SI I	6145.020	5.61	3.194E-02	-0.54	-0.85	-0.73	-----	-0.84	-0.31
SI I	6155.142	5.62	9.052E-02	-0.58	-0.47	-0.25	-----	-0.31	-0.20
SI I	7849.973	6.19	2.161E-01	-0.70	-1.11	-----	-0.77	-----	-0.50
SI I	7932.354	5.96	2.873E-01	-0.61	-0.53	-----	-0.66	-----	-0.28
SI I	8728.021	6.18	5.329E-01	-0.90	-1.14	-----	-1.25	-----	-----
SI I	8752.022	5.87	2.418E-01	-0.51	-0.64	-----	-0.62	-----	-----
CA I	6156.019	2.51	2.812E-03	-0.29	-0.45	-0.47	-----	-0.12	-0.44
CA I	6161.294	2.51	4.365E-02	----	-----	-0.36	-----	-0.42	-0.57
CA I	6166.439	2.51	4.741E-02	-0.09	-0.51	-0.20	-----	-0.43	-0.55
TI I	6121.006	1.88	5.182E-02	-0.30	-0.59	-0.64	-----	-0.76	-0.63
TI I	6126.224	1.07	4.112E-02	-0.32	-0.48	-0.67	-----	-0.69	-----
TI I	6138.430	2.15	1.563E-01	-0.60	-0.91	-0.62	-----	-1.13	-----
TI I	6146.235	1.87	2.961E-02	-0.25	-0.42	-----	-----	-0.44	-0.46
TI I	7852.680	0.85	1.349E-03	-0.06	-0.13	-----	-0.09	-----	-0.42
TI I	7949.159	1.50	3.337E-02	-0.24	-0.45	-----	-0.30	-----	-0.77
TI I	8675.382	1.07	2.507E-02	-0.51	-0.74	-----	-0.62	-----	-----
TI I	8682.990	1.05	1.489E-02	-0.45	-0.61	-----	-0.44	-----	-----
TI I	8692.343	1.05	5.675E-03	-0.21	-0.43	-----	-0.22	-----	-----
TI I	8734.707	1.05	9.333E-03	-0.60	-0.76	-----	-0.65	-----	-----
SC II	6300.684	1.50	1.300E-02	-0.89	-0.64	-----	-0.39	-----	-----
SC II	6320.843	1.49	1.268E-02	-0.81	-----	-----	-0.52	-----	-0.42
V I	6119.532	1.06	4.218E-01	-0.46	-0.90	-0.80	-----	-0.76	-0.97
V I	6135.370	1.05	2.250E-01	-0.58	-0.85	-0.81	-----	-0.70	-----

TABLE 2 (cont.)

	WAVELENGTH	EPLOW	GF(SOLAR)	I	A4	1-21	1-46	1-53	ARCTURUS
FE I	6120.249	0.91	2.131E-06	-1.09	-1.10	-0.99	-----	-0.94	-0.97
FE I	6127.912	4.12	4.523E-02	-0.67	-1.18	-0.95	-----	-1.08	-0.94
FE I	6147.834	4.07	3.812E-02	-1.12	-1.25	-1.02	-----	-1.09	-0.83
FE I	6151.621	2.17	4.413E-04	-0.73	-1.22	-0.88	-----	-0.94	-0.93
FE I	6157.733	4.06	3.966E-02	-0.45	-0.50	-0.58	-----	-0.75	-0.50
FE I	6165.304	4.12	2.162E-02	-0.58	-0.82	-0.74	-----	-0.58	-0.55
FE I	6173.343	2.21	7.768E-04	-0.71	-0.95	-0.63	-----	-0.70	-0.81
FE I	6353.840	0.91	4.882E-07	-0.70	-1.02	-----	-1.00	-----	-----
FE I	6355.035	2.85	5.508E-03	-1.04	-0.90	-----	-0.95	-----	-0.61
FE I	6380.748	4.17	3.371E-02	-0.98	-0.75	-----	-0.93	-----	-0.74
FE I	6392.542	2.28	7.742E-05	-0.63	-0.70	-----	-0.71	-----	-0.68
FE I	7807.913	4.99	4.200E-01	-1.01	-1.10	-----	-1.19	-----	-0.94
FE I	7855.401	5.06	8.672E-02	-0.56	-0.79	-----	-0.74	-----	-0.65
FE I	7912.871	0.86	1.637E-05	-1.05	-0.95	-----	-0.95	-----	-1.08
FE I	7924.150	4.79	2.685E-02	-1.05	-0.95	-----	-0.72	-----	-0.30
FE I	7941.095	3.27	3.400E-03	-1.04	-1.01	-----	-1.09	-----	-0.76
FE I	8607.075	5.01	4.749E-02	-1.07	-0.80	-----	-1.11	-----	-----
FE I	8610.609	4.43	2.113E-02	-1.04	-0.95	-----	-1.18	-----	-----
FE I	8611.813	2.84	1.692E-02	-1.62	-1.62	-----	-1.74	-----	-----
FE I	8616.284	4.91	1.231E-01	-1.26	-1.21	-----	-1.27	-----	-----
FE I	8621.611	2.95	7.691E-03	-1.34	-1.39	-----	-1.51	-----	-----
FE I	8671.879	5.02	3.031E-02	-0.49	-0.70	-----	-0.74	-----	-----
FE I	8674.756	2.83	2.650E-02	-1.43	-1.53	-----	-1.42	-----	-----
FE I	8729.153	3.41	1.778E-03	-0.95	-1.16	-----	-1.24	-----	-----
FE I	8747.432	3.02	5.011E-04	-0.82	-1.01	-----	-0.95	-----	-----
FE I	8757.198	2.84	1.192E-02	-1.35	-1.45	-----	-1.45	-----	-----
FE I	8763.976	4.65	6.379E-01	-1.34	-1.49	-----	-1.38	-----	-----
FE I	8698.717	2.99	6.233E-04	-1.13	-1.22	-----	-1.20	-----	-----
FE I	8699.461	4.95	4.626E-01	-1.34	-1.11	-----	-1.29	-----	-----
FE II	6149.249	3.89	1.662E-03	-1.25	-1.12	-0.86	-----	-1.28	-0.50
FE II	6369.419	2.89	6.568E-05	-1.21	-0.93	-----	-1.32	-----	-----
NI I	6128.984	1.68	4.161E-04	-0.87	-0.90	-0.64	-----	-0.97	-0.69
NI I	7797.589	3.90	6.824E-01	-1.31	-1.37	-----	-1.39	-----	-0.98
NI I	7861.037	3.70	1.431E-02	-0.95	-0.94	-----	-0.93	-----	-0.54
NI I	7863.792	4.54	1.146E-01	-0.62	-0.66	-----	-0.60	-----	-0.46
NI I	8702.499	2.74	1.109E-03	-1.00	-0.90	-----	-1.00	-----	-----
NI I	8770.688	2.74	1.373E-03	-0.87	-1.04	-----	-0.91	-----	-----
CU I	7933.130	3.78	4.449E-01	-1.10	-0.95	-----	-0.83	-----	-0.39
RB I	7947.630	0.00	6.500E-01	-0.37	-0.53	-----	-0.45	-----	-0.96
ZR I	6127.475	0.15	8.640E-02	-0.53	-0.99	-0.84	-----	-0.78	-1.23
ZR I	6134.710	0.00	5.300E-02	-0.64	-1.02	-0.87	-----	-0.85	
ZR I	6143.183	0.07	7.910E-02	-0.64	-0.94	-1.00	-----	-0.82	
ZR I	7849.380	0.69	5.040E-02	-0.43	-0.65	-----	-0.54	-----	-0.94

Table 3

Iron Abundances in M71 and Arcturus.

Star	All lines [Fe/H] HM	All lines [Fe/H] BEGN	All lines [Fe/H] CT	Lines in Common [Fe/H] HM	Lines in Common [Fe/H] BEGN	Lines in Common [Fe/H] CT
I	-0.99	-0.74	-0.79	-0.84	-0.59	-0.59
A4	-1.06	-0.81	-0.87	-0.95	-0.70	-0.71
1-21	-0.83	-0.58	-0.56	-0.83	-0.58	-0.56
1-46	-1.13	-0.87	-0.97	-0.92	-0.67	-0.73
1-53	-0.87	-0.62	-0.62	-0.87	-0.62	-0.62
M71 Mean*	-0.98	-0.73	-0.76	-0.88	-0.63	-0.64
M71 Mean**	-0.90	-0.65	-0.66	-0.85	-0.60	-0.59
Arcturus	-0.75	-0.50	-0.55	-0.75	-0.50	-0.55

Note:
HM.....Holweger and Muller Solar Model
BEGN...Bell et. al. Solar Model
CT.....Corlis and Tech (corrected) theoretical gf values
*......All stars in M71
**.....The three hottest stars in M71

Table 4

Abundances of Various Elements Relative to Iron in the M71 Stars and Arcturus

	M71			Arcturus		
Elements	HM	BEGN	[X/H]	HM	BEGN	[X/H]
O I	-----	-----	-0.61	-----	-----	-0.16
Na I	+0.60	+0.49		+0.29	+0.18	
Mg I	+0.47	+0.33		-----	-----	
Al I	+0.57	+0.43		+0.51	+0.37	
Si I	+0.22	+0.07		+0.43	+0.28	
Ca I	+0.55	+0.61		+0.23	+0.29	
Ti I	+0.34	+0.27		+0.18	+0.11	
Sc II	+0.23	+0.11		+0.33	+0.21	
V I	+0.15	+0.04		-0.22	-0.33	
Fe II	-0.26	-0.34		+0.25	+0.17	
Ni I	-0.02	-0.07		+0.08	+0.03	
Cu I	-0.08	-0.23		+0.36	+0.21	
Rb I	-----	-----	-0.45		-----	-0.96
Zr I	-----	-----	-0.76	-----	-----	-1.09
La II	-0.10	-0.22		-----	-----	

Note:

For O I, Rb I, Zr I we used absolute f-values. Hence, we list the ratio to hydrogen, not iron.

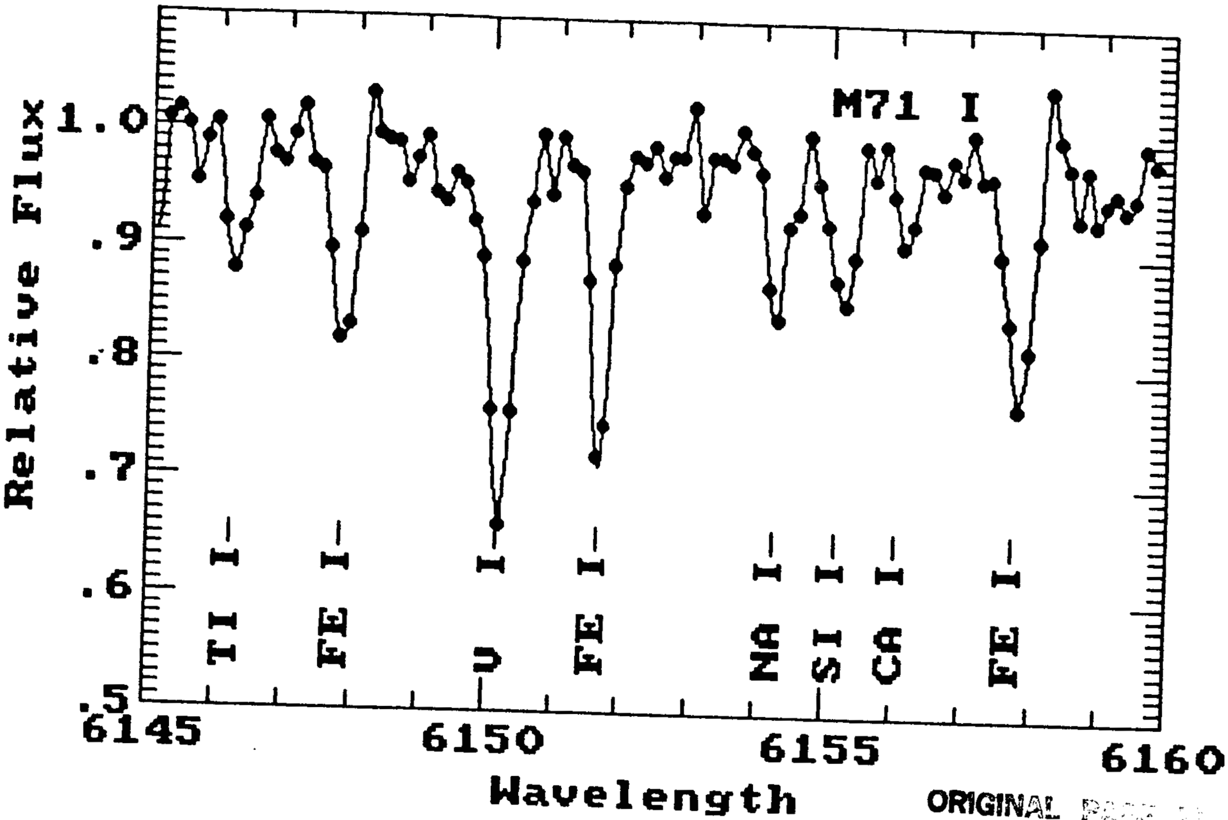
HM....Holweger and Muller Solar model

BEGN..Bell et.al. Solar model

Figure Captions

Figure 1. Palomar CCD spectra of M71, Star I, and Arcturus at a resolution of 0.3 Å. The S/N is 50 for M71, I, and 260 for Arcturus. The observed points are shown, as well as a smooth fit produced by Lagrangian interpolation.

Figure 2. The relationship between N/H and C/H for three stars in M71. The dashed line is for star 1-46 and the solid line is for stars A4 and I. Also shown are the lines for C=N and C=3N, which are reasonable limits for moderately metal-poor stars. In addition, we show the likely main sequence abundances, assuming C/H = N/H = Fe/H.



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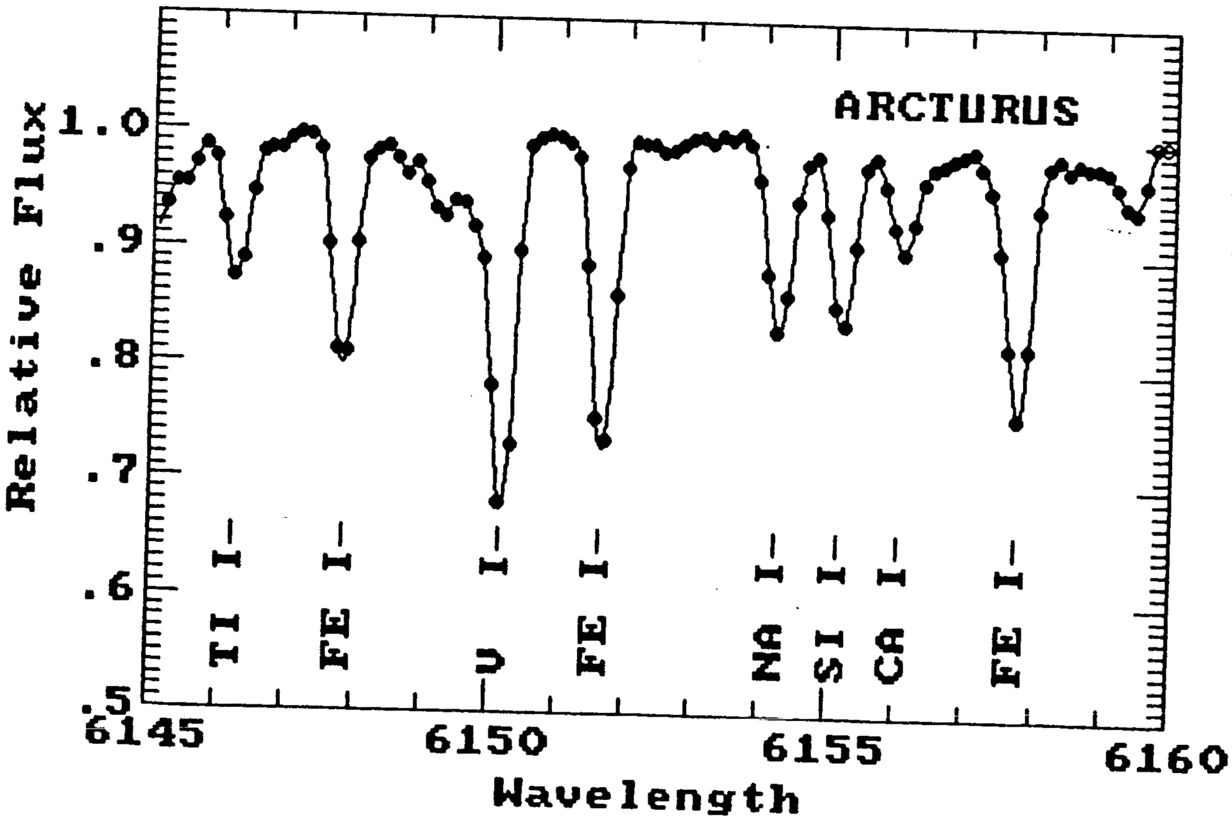

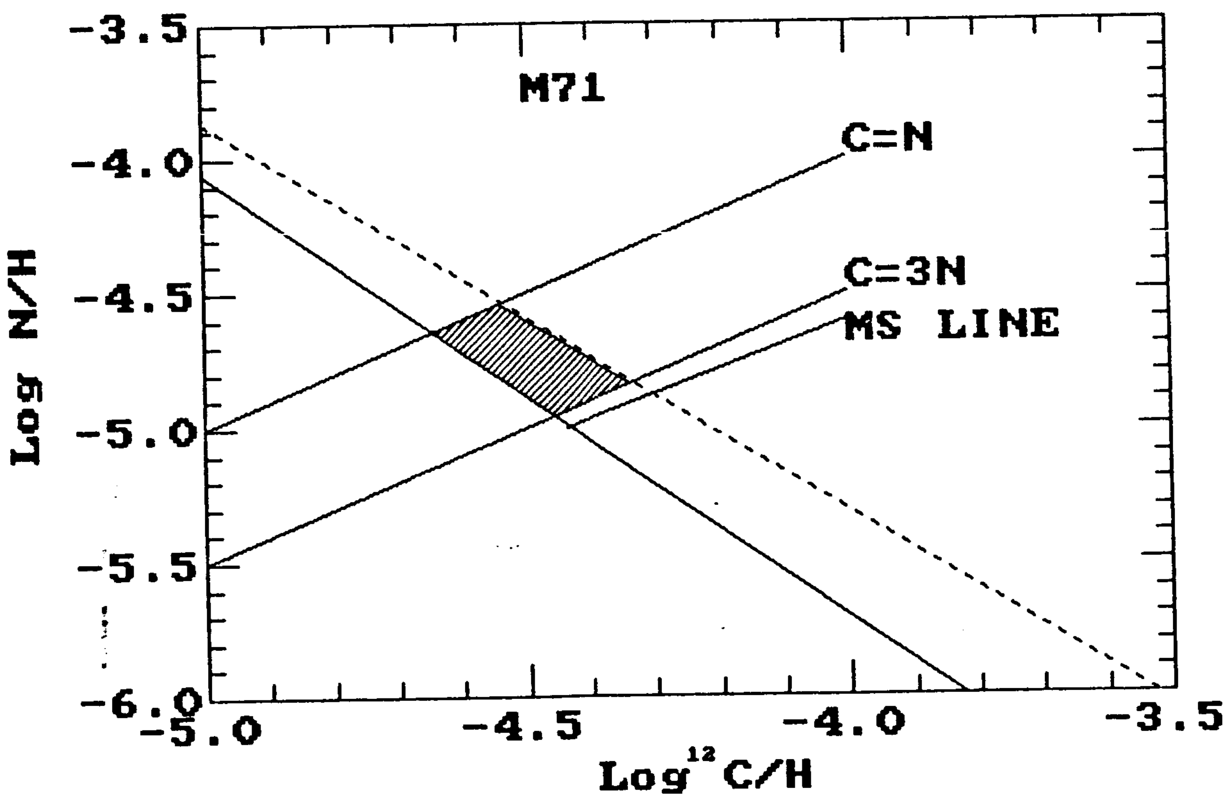

M71
C=N
C=3N
MS LINE
-3.5
-4.0
-4.5
-5.0
-5.5
-6.0
Log N/H
-5.0
-4.5
-4.0
-3.5
Log ^{12}C/H